CAVES AS TERRESTRIAL ANALOGS FOR MAPPING AND EXPLORATION IN PLANETARY SURFACE AND SUBSURFACE ENVIRONMENTS. W. E. King[1], M. R. Zanetti[1], E. G. Hayward[1], K. A. Miller[1], C. J. Whetsel[1] [1]NASA Marshall Space Flight Center. 4600 Rideout Road, Huntsville, AL 35812, USA. (walter.e.king@nasa.gov).

Introduction: The Kinematic Navigation and Cartography Knapsack (KNaCK) team is developing tools that will enable ultra-high resolution terrain mapping and navigation at the lunar surface. KNaCK uses mobile light detection and ranging (LiDAR) and simultaneous localization and mapping (SLAM) algorithms to operate in fully GPS-denied and unilluminated environments [1, 2]. Testing in relevant analogs is key to perfecting this technology for planetary applications. After utilizing desert and volcanic environments for multiple tests, the team is now using caves as an additional proving ground. Tests in terrestrial caves have demonstrated the potential of mobile SLAM LiDAR for use in challenging surface environments such as steep walled craters and permanently shadowed regions as well as for lunar, planetary, and terrestrial cave exploration, study, and utilization.

Mobile LiDAR as a Tool for Science: Mobile LiDAR is easy to operate, sees beyond the cast of visible light, can function without GPS, and produces rapid and incredibly detailed surveys. Manual survey techniques based on heading and inclination measurements may work without GPS, but they do not capture a comparable level of detail and are not suitable for planetary applications [3]. Mobile LiDAR can reach into inaccessible or dark and shadowed features such as pits and craters and characterize what lies within them.

Fig. 1. *(left) Mare Tranquilitatis Pit, Oceanus Procellarum, Moon. (right) Skylight in Three Caves, Huntsville, AL. USA, Earth.*

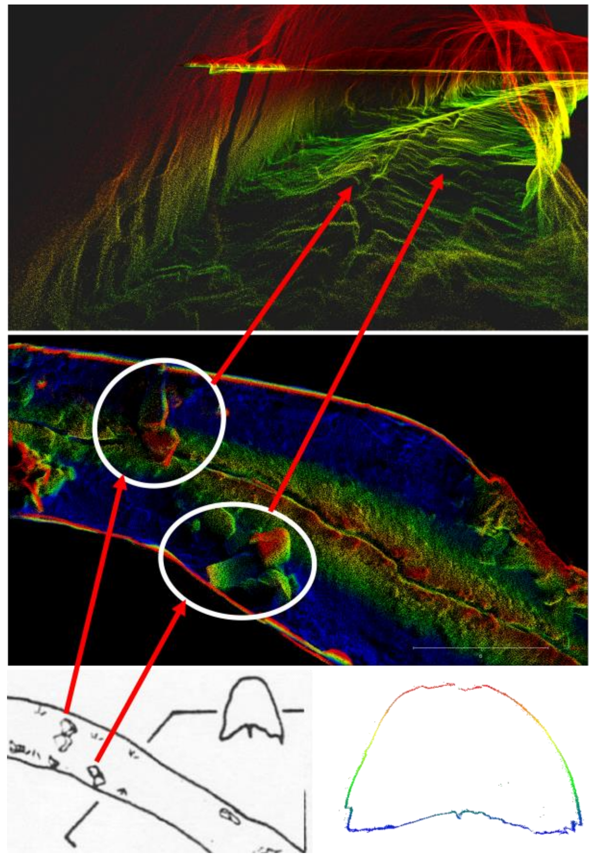

Fig. 2. *SLAM LiDAR captures every detail at cm-scale: (bottom left) Paper cave map excerpt. (top and middle) LiDAR shows corresponding features and additional detail not included in the paper map. (top) Features can look very different from other perspectives. (lower right) Cross-section of passage derived from the LiDAR point cloud.*

The detailed 3D spatial data collected with mobile LiDAR has many applications. The data is useful as an input to simulations such as heat transfer models and radiation transport models. Data collected with the KNaCK instrument has already been used for the latter purpose [4]. The morphology captured by mobile LiDAR can also offer insights into the geologic history of planetary bodies as well as holds promise for investigations of costal erosion, volcanism, and cave science here on Earth.

Caves as Terrestrial Analogs: The lunar surface has rugged and irregular terrain, difficult illumination conditions (extremely low angle of incidence sunlight),

and no access to GPS. Lava tubes and subsurface voids on the Moon, Mars, and other planetary bodies present similar challenges. Terrestrial caves are excellent analogs for these conditions, providing an opportunity to refine technology for mobile mapping and navigation on other worlds while advancing the State of the Art for cave survey on Earth (Fig. 2). The overburden above cave passages blocks ingress of both light and GPS signals. Highly irregular geometry challenges scan matching algorithms and frequent jostling of the instrument due to rugged and confined terrain interferes with the accuracy of dead reckoning based on inertial measurements. Many terrestrial caves have also been mapped by other means. This data provides a ground truth that can be used to quantify system performance. Other technology development efforts and science investigations may find caves to be useful analogs for similar reasons.

Field Work: The KNaCK instrument was used to map two terrestrial caves: Three Caves in Huntsville, AL, and Lava River Cave, a lava tube in northern AZ. Data from Three Caves was collected in 6.5min, capturing a substantial portion of a maze-like complex with only a 370m traverse. Data from Lava River Cave was collected in 44min over 1100m. The maps produced contain 18.4M and 44.8M points, respectively, after post-processing.

Results: The accuracy of the Lava River Cave scan was compared to a previous survey of the cave produced by the Central Arizona Grotto (Fig. 3). The LiDAR map is highly accurate at local scale, recording the morphology of the cave in cm-scale detail (Fig. 2). However, there is considerable drift from the previous survey at global scale. Through continued testing in cave environments, the team aims to produce surveys that still retain incredible detail while improving global accuracy by tuning SLAM parameters and experimenting with constraining solutions with other data sets (such as manual survey data or radio location stations). A comparison of the void volume derived from the manual cave survey methods and the mobile LiDAR scan is planned.

Summary: Mobile LiDAR can provide information about features that would be difficult or impossible to attain otherwise. Caves have provided the KNaCK team with a challenging and relevant environment in which to demonstrate the utility of mobile LiDAR as a tool for characterizing and studying planetary environments. The responsible use of terrestrial caves as analogs could likely benefit a wide array of other technology development efforts and science investigations as well.

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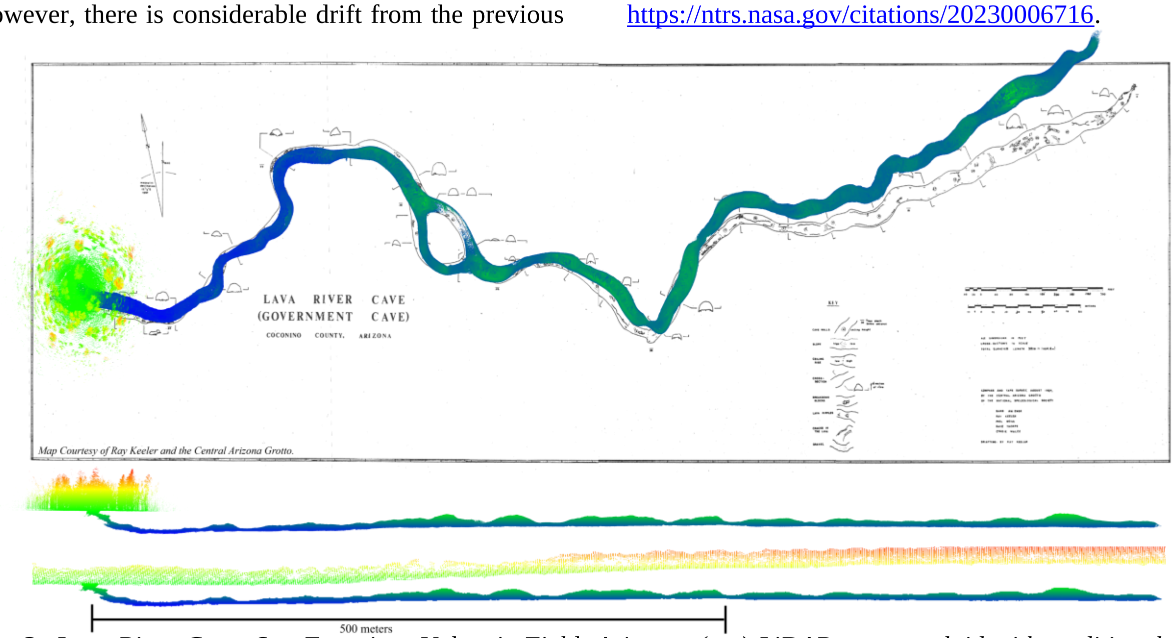

Fig. 3. *Lava River Cave, San Francisco Volcanic Field, Arizona: (top) LiDAR map overlaid with traditional cave map, (middle) profile view of LiDAR map, (bottom) NAIP Point Cloud DEM overlaid with LiDAR map*.